Planetary-scale inertio gravity waves in the Mesosphere

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[1] In the polar region of the upper mesosphere, horizontal wind oscillations have been observed with periods around 10 hours. Waves with such periods are generated in our Numerical Spectral Model (NSM), and they are identified as planetary-scale inertio gravity waves (IGW). These waves have periods between 9 and 11 hours and appear above 70 km in the zonal mean (m = 0), as well as in m = 1 to 4 propagating eastward and westward. They grow in magnitude to altitudes near 100 km and have vertical wavelengths of about 25 km. The m = 1 westward IGWs have the largest amplitudes, up to 30 m/s at the poles. The IGWs occur intermittently but reveal systematic seasonal variations. Their amplitudes generally are largest in late winter and spring. Numerical experiments show that the waves also appear without tidal excitation. Like the planetary waves in the model, the IGWs are produced by instabilities that arise in the mean zonal circulation. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3332 Meteorology and Atmospheric Dynamics: Mesospheric dynamics; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3367 Meteorology and Atmospheric Dynamics: Theoretical modeling; 3384 Meteorology and Atmospheric Dynamics: Waves and tides. **Citation:** Mayr, H. G., J. G. Mengel, E. R. Talaat, H. S. Porter, and K. L. Chan, Planetary-scale inertio gravity waves in the Mesosphere, *Geophys. Res. Lett.*, *30*(23), 2228, doi:10.1029/2003GL018376, 2003.

1. Introduction

[2] Based on optical measurements, *Hernandez et al.* [1992] observed a pronounced oscillation in the horizontal winds with a period of 10.1 hours near the South Pole. Radar measurements from the Scott Base at 78°S [*Fraser*, 1984] provided additional observations. During August 1991, the 10-hour wave dominated at the South Pole, but the semidiurnal tide was stronger at 78°S. Horizontal winds at the pole must have zonal wavenumber m = 1, and the wave was observed propagating westward. The related temperature variations for m = 1 must vanish at the pole, and this was confirmed for the observed oscillation period.

[3] *Hernandez et al.* [1993] again observed the 10-hour oscillation during the winter of 1992 in the antarctic polar region, but it was accompanied by a westward 12-hour wave of comparable magnitude they called an inertio gravity wave. *Forbes et al.* [1995] also observed a 12-hour wave in radar measurements near the North Pole and classified it as a non-migrating semi-diurnal tide.

[4] We shall show that our model produces in the upper mesosphere waves with periods around 10 hours such as observed by *Hernandez et al.* [1992, 1993]. The oscillations are identified as planetary-scale inertio gravity waves (IGW).

2. Numerical Spectral Model

[5] The Numerical Spectral Model (NSM) was introduced by *Chan et al.* [1994a], and 2D as well as 3D applications were used to describe the equatorial oscillations (QBO and SAO), and the tides and planetary waves in the middle atmosphere [e.g., *Mengel et al.*, 1995; *Mayr et al.*, 1998, 2001, 2003].

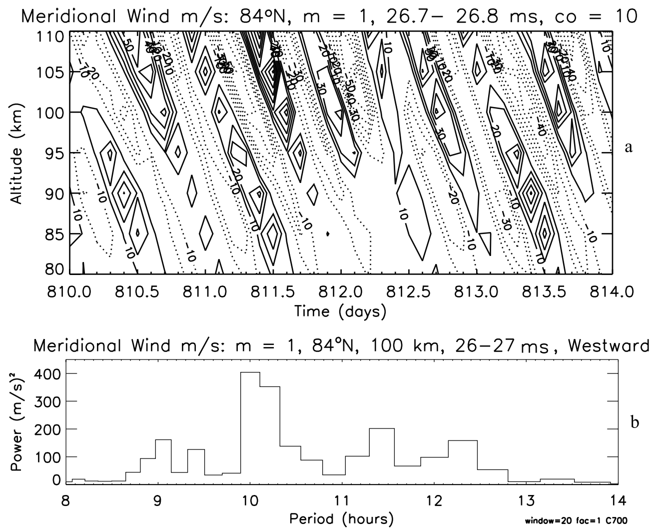

Figure 1. (a) Time-altitude contour plot of meridional winds for zonal wavenumber m = 1 at 84°N (Gaussian point) during March (late northern winter) of the 3rd model year (26 to 27 months), when the 10-hour wave dominated at polar latitudes. (To reduce output, the results are recorded with 5 km altitude interval, which causes the contours to appear ragged.) (b) For a window of 20 days, which includes the time span of (a), the power spectrum of the dominant westward waves is shown at 100 km. This reveals a maximum amplitude of about 20 m/s for the 10-hour wave, larger than that of the non-migrating 12-hour tide. The model simulation thus resembles the situation encountered by *Hernandez et al.* [1992] during austral winter of 1991.

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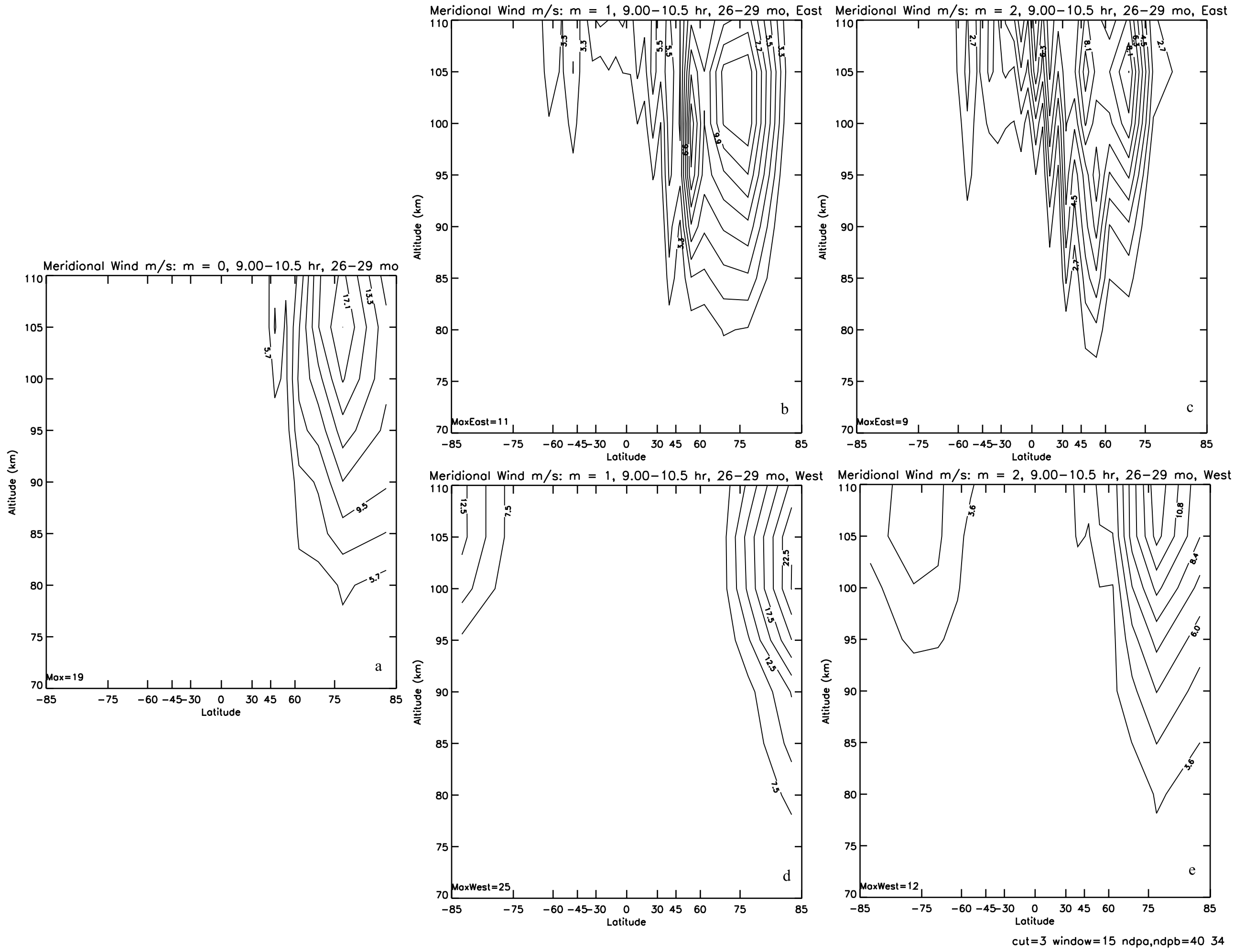

Figure 2. Maximum meridional wind amplitudes of stationary m = 0 wave (a), and eastward (b, c) and westward (d, e) waves (m = 1, 2) for periods from 9 to 10.5 hours, computed with a running window of 15 days from the time span of 26 to 29 months (March through May of 3rd model year). The Mercator projection is applied to expand the regions at high latitudes where the waves are prominent. The lowest 30% of contours are suppressed to eliminate clutter, and the maximum amplitudes are recorded in each panel.

[6] The NSM incorporates the Doppler Spread Parameterization (DSP) for small-scale gravity waves [*Hines*, 1997a, 1997b]. To resolve the wave interactions, the model has a vertical step size of 0.5 km below 120 km altitude. The maximum meridional and zonal wavenumbers are respectively l = 12 (12 Gaussian points per hemisphere) and m = 4 (16 longitude points).

[7] The 3D version of the NSM employed here differs from earlier applications in that we incorporate tropospheric heating for the zonal mean (m = 0) to reproduce qualitatively the observed zonal jets and temperature variations near the tropopause.

3. Model Results

[8] With Figure 1a we show the computed meridional winds for zonal wavenumber m = 1 at 84°N for altitudes between 80 and 110 km, covering a time span of 4 days in March of the 3rd model year. This time interval contains waves with periods close to 10 hours, which propagate upward with vertical wavelengths of about 20 km. Shown in Figure 1b is a power spectrum histogram (amplitude squared) of the dominant m = 1 westward waves at 100 km for a 20-day time span in March (that includes the 4-day range of Figure 1a). A 10-hour wave predominates that is larger than the non-migrating semi-diurnal tide. This scenario is atypical but resembles the observations of *Hernandez et al.* [1992]. A limited survey of our simulations reveals that a similar situation (not shown) also occurs for m = 1 in the southern hemisphere during September of the 3rd model year when a 9-hour wave appears with amplitude exceeding 20 m/s, larger than the 14 m/s of the non-migrating semi-diurnal tide near the South Pole.

[9] In Figure 2 we show, for wavenumbers m = 0 to 2, the maximum amplitudes of the stationary wave (a) and the eastward (b, c) and westward (d, e) waves of the meridional winds with periods between 9 and 10.5 hours, derived with a running window of 15 days from the time interval March through May. Both eastward and westward waves are produced. The m = 1 westward wave is largest with a peak

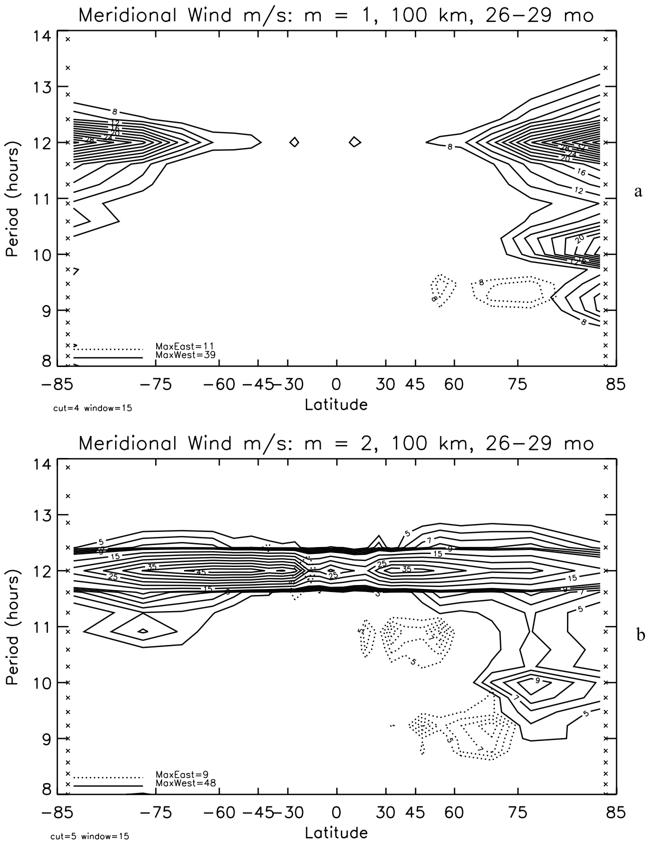

Figure 3. Maximum amplitude spectra for zonal wavenumbers m = 1 (a) and 2 (b) at 100 km for periods between 8 and 14 hours, computed with a running window of 15 days from the 26 to 29 months time span (March through May). Solid and dotted contours describe respectively the westward and eastward components. In (a) the lowest contour is 8 m/s, in (b) it is 5 m/s. In (b), the contour intervals are variable to resolve the large migrating tide. Note the non-migrating semi-diurnal tide (12-hour period) at m = 1 that peaks at the poles (a), which is produced in the NSM through non-linear interaction between the solar driven semi-diurnal migrating tide and stationary m = 1 planetary waves as *Forbes et al.* [1995] had proposed.

of 25 m/s near 100 km. Unique for wavenumber m = 1, the amplitudes do not vanish at the poles but can peak there. Temperature variations can also occur at the poles but only for m = 0, and during March, a 9-hour oscillation dominated in the arctic having amplitudes of about 6 K at 100 km. As Figure 2 indicates, for the three wavenumbers, the largest waves are generated in the winter hemisphere approaching equinox (i.e., during late winter and spring).

[10] To provide more details we present in Figure 3 contour plots of amplitude spectra at 100 km for wavenumbers m = 1 and 2. Respectively, the lowest 40% and 50% of the contours are suppressed to eliminate clutter. For m = 1 (Figure 3a), the non-migrating semi-diurnal tide is prominent in both hemispheres. The 10-hour wave is weaker but still significant (24 m/s at 84° latitude). A 9-hour wave is also present, with peak amplitude 14 m/s. The latitude dependence of these two westward propagating waves suggest that they reach still larger values at the north pole. In contrast to that, the weaker eastward wave (dotted lines), with 10 m/s amplitude, does not extend into the polar region. For m = 2, we show in Figure 3b the large westward migrating semi-diurnal tide with a peak close to 45 m/s. In the northern hemisphere, a distinct westward wave appears with period close to 10 hours and two eastward waves with periods close to 9 and 11 hours.

[11] The latitudinal variations of the waves are presented in Figure 4, which shows in the southern hemisphere contours of snap-shots of the eastward (a) and westward (b) components for a short time span near 32.5 months (mid September). The horizontal wavelengths are about 40° in latitude, and the vertical wavelength of about 25 km is similar to that shown in Figure 1.

4. Discussion and Conclusion

[12] The waves described here appear to be related to the Class I waves discussed by *Longuett-Higgins* [1968], which are also referred to as Gravity Waves or Inertio Gravity Waves [*Volland*, 1988; *Andrews et al.*, 1987]. Considering that the waves have zonal wavenumbers m = 0 to 4, we refer to them as planetary-scale inertio gravity waves (IGW). Since the Coriolis force is important for these waves, one expects that the eastward and westward components differ significantly. For m = 1, the westward Class I waves of *Longuett-Higgins* [1968] peak at the poles, while the eastward waves tend to peak at mid latitudes. This is

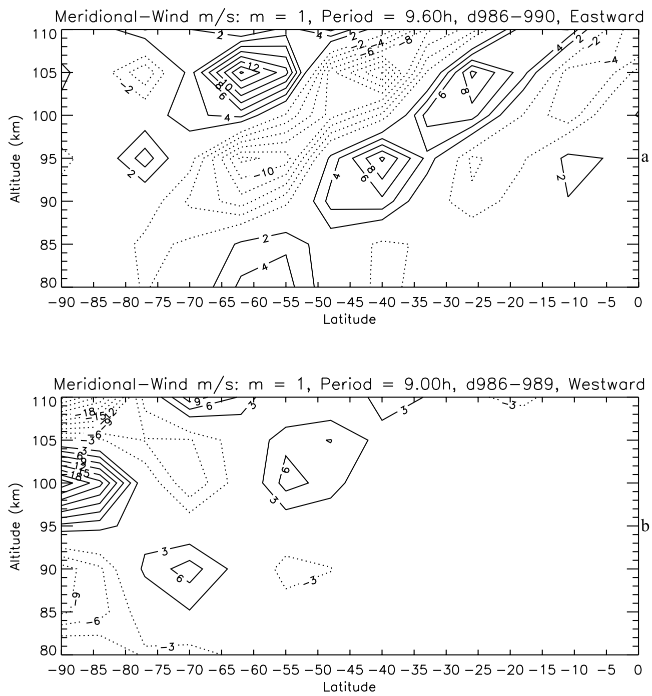

Figure 4. Snap-shots of meridional winds in the southern hemisphere near 32.5 months (mid September) when the waves are most prominent. The winds are derived from short time spans of 3 and 4 days respectively for the 9- and 9.6-hour westward and eastward waves. (Recorded with 5 km intervals, the contours appear ragged.) The characteristic differences between the eastward and westward components are evident, each revealing a horizontal wavelength of about 40° latitude. The vertical wavelength is about 25 km.

consistent with the numerical results presented (Figures 2, 3 and 4). The latitudinal structures of the prominent waves have horizontal wavelengths of about 40° (Figure 4), which suggests that they are related to Class I waves with meridional wavenumber of about n $\approx$ 360/40 $\approx$ 9. Classical Hough modes for the 5th or 6th symmetric and antisymmetric modes correspond roughly to the horizontal structure seen in the model wind field, and they have vertical wavelengths (by courtesy of Elsayed R. Talaat) comparable to those generated (about 25 km) for oscillation periods between 9 and 11 hours. Since our model describes a number of processes not accounted for in classical theory (e.g., eddy viscosity and gravity wave drag), one would not expect "clean" individual Hough modes to be generated.

[13] Numerical experiments reveal that the IGWs still appear without tidal excitation. The waves then differ in detail but have similar periods and magnitudes. When the solar heating that drives the zonal mean (m = 0) circulation (and associated variations in temperature and pressure) is turned off, the IGWs and planetary waves (PWs) disappear. The baroclinic instability was proposed by *Plumb* [1983] to generate the 2-day PWs in particular, and *Chan et al.* [1994b] proposed that it produced the 4-day wave in their model.

[14] The IGWs have periods between 9 and 11 hours, and they reproduce some of the features of the 10-hour wave observed by *Hernandez et al.* [1992, 1993]. The largest amplitudes occur in late winter and early spring and at polar latitudes in the westward wave for m = 1. Our IGWs however have vertical wavelengths of about 25 km (Figures 1 and 4), which is much shorter than the 100 km wavelength inferred by Hernandez et al. that led them to conclude they were observing a Lamb wave. As a reviewer reminded us, the vertical wavelength Hernandez et al. observed may be uncertain because of the limited altitude coverage of the radar. Alternatively, their wave may have had a lower meridional wavenumber than ours.

[15] Inertio gravity waves have been observed with MST (Mesosphere, Stratosphere, Troposphere) radars [e.g., *Fritts et al.*, 1984; *Muraoka et al.*, 1988, 1994; *Tsuda et al.*, 1989]. These waves have periods typically between 5 and 11 hours and horizontal wavelengths between about 500 and 3000 km. With horizontal propagation velocities close to the background zonal winds, these waves are subject to critical level absorption, as evidenced by the altitude invariance of their observed amplitudes. Inertio gravity waves of this kind thus represent the long-period component of the saturated gravity wave spectrum that characterizes the middle atmosphere [*Fritts*, 1984].

[16] The planetary-scale inertio gravity waves discussed in the present paper differ from the above inertio gravity waves in that their horizontal wavelengths and propagation velocities are much larger. These IGWs thus propagate through the background circulation without much breaking and grow in magnitude throughout the upper mesosphere.

[17] **Acknowledgments.** The authors are indebted to two anonymous reviewers for valuable comments.

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